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USING DOMAINS TO CONSTRAIN DESIGN VARIABLES

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ABSTRACT

Design is a difficult, complex subject. Many believe that it can only be learned by doing – gaining experience by designing artefacts. In this paper we propose that experienced designers make their life simpler by implicitly recognizing that their design problem lies within a context and by recognizing the particular context in which a problem lies. In our view context include such things as the branch of industry, the country, the company, the domain of the problem and the functions, objectives, constraints and design principles involved in the design problem. Implicitly recognizing the context simplifies the problem by constraining the number of variables. In particular the part of the context formed by the domain of the problem constrains the number of flows (the nouns associated with the active verb functions) and functions (i.e. active verbs that are relevant to that problem. We present a series of taxonomies that decompose the engineering domain down to sub-sub-sub-domains and show that both the nouns and the action verbs are constrained within the sub-sub-sub-domains by a large percentage (>50%). We discuss the implications of this finding for a variety of topics including design education and design automation.

1 INTRODUCTION AND BACKGROUND

Product design has become a complex task with designers requiring substantial experience and knowledge to perform it efficiently and in a timely manner. To simplify the process of design and to understand it better, many design researchers have proposed various design taxonomies. These taxonomies present a macroscopic view of design by providing either an organization of the various types of mechanical design problems [1], a near complete classification of the elements in the domain of mechanical design [2], a classification of design tasks or an organization of the design variables such as functions and flows [3]. While these taxonomies are highly valuable we believe that they are only part of a larger concept, namely the context surrounding design.

The objective of our research is to understand the importance, use and influence of context in design. Some of our ideas on the usefulness of context in design are presented elsewhere [4]. Our view at this time is that by understanding the nature of context in design we should be able to identify ways in which it can be used in teaching, mentoring inexperienced designers (i.e. overcoming their lack of experience) and in eventually devising automated systems that can "do design". This is our long range goal. While some of what we present below may seem obvious, we believe that this paper is a first step towards achieving this goal. It is not our intent in this paper to present a complete picture of how context impacts and influences design and the design process. What we present here is a work in progress towards a fuller understanding of the impact of context on design.

Context is a multifaceted, complex and difficult topic, yet we use this powerful tool in our daily lives implicitly and without effort all the time. The nature of context has been studied in numerous domains e.g. Artificial Intelligence where lack of context awareness has been cited as the reason for many of AI's failures [5]. There are numerous definitions of context which include a) any identifiable configuration of environmental, mission-related, and agent-related features that has predictive power for behavior [6]; b) context is what constrains a problem solving without intervening in it explicitly [7]; c) contextual information of a process is information whose value remains constant during processing and changes when the process is used for another application [8]; d) the delimitation of a domain, that allows to restrict the possible solution-space of a problem [9]; e) any information that can be used to characterise the situation of an entity [10]; (f) a context surrounding an entity of interest is a set of properties (with values), that are (i) provided by a set of entities in the same symbolic or physical space as the entity of interest, (ii) relevant to the entity of interest in that situation of interest during some time interval and (iii) added to the properties of that entity only within that context [11]. We will not discuss these here further here for lack of space but refer the reader to the excellent review by Brezillon and Pomerol [7] who note that context delimits the problem space.

It is generally recognized that design is predominantly a problem solving activity. It can also be assumed that all design is performed in some context viz. the environment, participants, their characteristics and resources, the domains along with traditional design factors (objectives, constraints, functions, flows and solutions) etc. We suggest that these factors form the context surrounding the design problem. This context is useful because, in our opinion, when presented with a design problem, experienced designers implicitly define the design context thereby delimiting the design problem space. Following Sowa's convention we structure context into three levels: 1) *pragmatic or external*, 2) *semantic* or *internal*, and 3) *syntax* [12].

Our view of the structure of the design context is as follows. The *external* design context consists of the environment, including the participants, their characteristics and resources. This recognition delimits their problems to those of their company, their country, and their team. Two simple examples illustrate the idea of *external* design context: a designer in Ford Motor Company works under an entirely different external context than one in Boeing Aircraft Corporation while the designer in Ford has a different external context than one in Toyota Corporation. The parameters constrained in this external context include rules, regulations, guidelines, policies, procedures, tools, and techniques. The cultures, rules and regulations are different in each of the three companies and two countries. The policies, procedures, tools, techniques are also constrained by this context level. Our understanding of these has been formalized by various design theories put forward by [1] and [2].

In the syntax level, the design variables (i.e. objectives, constraints, other specifications) form a context that further constrains the available solutions. We do not discuss this any further in this paper but have discussed a preliminary model involving this elsewhere [13].

The *semantic* or *internal* design context consists of the domain, sub-domain, etc – the domain context - of the problem. The central thesis of this paper is that this context level delimits the flows, functions and perhaps even solutions for a design problem from a very large set to a manageable few. This constraining simplifies the design problem. This domain context is the area of focus of this paper.

We note at this juncture that we are using the term "flow" in the sense of Hirtz et al [14]. The term represents the nouns that are the entities on which the action verb – the function – acts.

In this paper we explore the idea that by identifying the domain context, we severely prune the number of flows that are available to the designer. The delimitation process does not stop at this point, however. Design researchers have also suggested that certain functions are limited to operate on certain types of flows. Hence these delimited flows then prune the relevant functions to a minimal number. To provide an example of this process, consider the Mechanical Engineering sub-domain and more specifically the Structures sub-sub-sub-domain. The flows that are relevant in this domain are Forces, Torques and Moments. With the knowledge of the domain, sub-domain and the flow we can eliminate functions such as Consume and Absorb, which are irrelevant as these functions typically apply to the flow "information".

Below we present our ideas on how this delimitation process proceeds. As a start we have defined several tables of sub-domains, sub-sub-domains and sub-sub-sub-domains within the domain of Engineering. These tables define the flows that are applicable at each level in the domain taxonomy. We then identify physical mathematical laws and principles that can be used to delimit functions associated with the flows. Our domain tables are based earlier taxonomies by other authors [14], [15].

The proposed taxonomies are intended to be as complete as possible as far as they go but there are more aspects to them then can be discussed here. We mention some briefly in the discussion section. We also present in this paper some examples that show how these taxonomies could be used thus helping to prove their usefulness.

2 APPROACH AND RESULTS

2.1 Domain contexts and flows

The first question that needs to be asked is: what are the domains of interest? It is not possible here to cover all domains, sub-domains, sub-sub-domains, etc in the engineering field. In this paper we explore the engineering domain and its sub-domains, with a particular focus on "Pure" Mechanical Engineering, defined later. When seeking methods to decide what flow or function belongs in a domain and what function can be associated with what flow there are two possibilities: ad-hoc decisions by the authors or decisions using some underlying principle or categorization scheme. We use underlying principles and categories.

Our overall approach follows a well known design procedure: top down decomposition. The first underlying principle is that domains form a taxonomy and that sub-domains and sub-sub-domains, etc., have one or more flows associated with them. Pahl and Beitz have categorized flows into three main classes: energy, material and signal or information [16]. We prefer the use of the term information rather than signal since it has a broader concept than signal. The domain of engineering tends to have the predominant primary flow of energy associated with it but there is some use of the flow, information, and the flow, material.

To decompose the sub domains we first use the traditional decomposition of engineering as might be found in any reasonably sized engineering college of a university. The result of decomposing the engineering domain into sub-domains is shown in Table 1.

Table I Illustrates the Classification of the Sub Domains

Domain	**Sub-Domain**	**Predominant flow**	**Subsidiary flows**
Engineering		Energy, Material, Information	
	Mechanical	Mechanical energy, Fluid energy, thermal energy,	Material, Information
	Aerospace	Mechanical energy, fluid energy	Material, Information
	Civil	Mechanical energy, fluid energy	
	Electrical	Electrical energy	
	Chemical	Material Chemical Energy	Information
	Petroleum	Material, Chemical energy	Information
	Nuclear	Nuclear energy, material	Information
	Industrial	Material and Information	Energy
	Software	Information	
	Computer	Electrical Energy and Information	
Sciences	Physics	Energy, material and information	
	Chemistry	Chemical energy, material and information	
	Biology	Biological energy	Information

Then using the flow taxonomy created by Hirtz, et al [14], we identify the predominant flow for each sub-domain. While we use Hirtz et al's [14] notation of the word "Flow" there are difficulties with this notation especially when discussing functions involving material and signals and electrical and electromagnetic energy which can "flow" from one point to another. We use the notation for consistency but remind the reader that when we provide a table of "flows" it is in Hirtz et al's sense of the noun associated with the active verb in the function, not in the sense of something actually flowing. Their flow taxonomy is based on the categorization of Pahl and Beitz mentioned above and is a consolidation of taxonomies by a number of authors. The reader is referred to Hirtz et al for details of the consolidation process [14]. We believe that at the present time, this taxonomy is the most complete source of functions and flows available. Hirtz et al's taxonomy has three levels: primary, secondary and tertiary with a set of correspondents for synonyms. The primary level is the same as that of Pahl and Beitz: Energy, Material and Information [16]. Table I presents the predominant primary flow associated with the domain and the secondary flows associated with the sub-domain. Subsidiary flows are our concept of which of the primary flows are subsidiary to the main primary flow in the sense that these flows are not usually problem solving areas for that sub-domain.

It is interesting to note that the decomposition of the engineering domain into traditional areas generally results in flows associated with the secondary level of flows in Hirtz et al's taxonomy of flows. We have included for comparison the field of Science at a high level. We note that the various engineering disciplines (the sub-domains) are closely related to a specific form of the energy flow: Electrical Engineering to electrical energy, etc. Indeed, we suggest that these disciplines are so called because of the predominant flow encountered in them. Industrial Engineering appears to be the exception.

It is evident from this decomposition that there is already some delimitation of the flows even at this high level. Each sub-domain can be further decomposed. In Mechanical Engineering the traditional decomposition is into what we call "Pure Mechanical Engineering (i.e. Structures and Mechanisms), Thermal Engineering, Fluids, Pneumatics, Materials, and Controls. This next level of decomposition follows the traditional one encountered in a specific engineering department such as Mechanical Engineering as shown in Table II.

Table II Decomposition of Mechanical Engineering into Sub-sub-domains and Sub-sub-sub-domains with Associated Flows.

Sub-Domain	**Sub-sub-domain**	**Sub-sub-sub-domain**	**Dominant Flows**
Mechanical Engineering	"Pure" Mechanical Engineering	Structures	Mechanical Energy, Forces, torques, moments
		Mechanisms	Mechanical Energy, Forces, torques, moments, rotational and translational motion
	Thermal engineering	HVAC,	Thermal energy, Temperature gradient, Heat flow, Pressure gradient, Gas flow
		Combustion	Thermal energy, Temperature gradient, Heat flow, Pressure gradient, Gas flow
		Heat transfer	Temperature gradient, Heat flow
	Pneumatics		Mechanical energy, Pressure gradient, Gas flow
	Fluids	Pressure vessels and piping	Mechanical energy, Pressure, Volumetric flow
	Materials		Materials, Information
	Controls	Mechanical	Information/ signals
		Electronic	Information/ signals

In this decomposition, we have ignored the newer mechanical engineering areas such as robotics, haptics, MEMS, etc. Our view is that these need further investigation and are outside the scope of this paper.

"Pure" Mechanical Engineering has two further subdivisions: Structures vs. Mechanisms. Structures have no motion flows but is associated with the flows shown, while Mechanisms have both motion flows and the forces, torques and moment flows. Both Structures and Mechanisms can have mechanical energy either as elastic energy due to deformation or potential energy due to gravity but only mechanisms can have kinetic energy due to motion.

In the Mechanical Engineering category of Hirtz et al's flow taxonomy, there are two tertiary categories, rotational and translational with four correspondents divided into two sub-categories: effort and flow [12]. If we pursue this decomposition then we end up with taxonomy leaves that have basically only one or two flows as illustrated in Table III.

From Hirtz et al, the flows associated with these two sub-sub-sub-domains are the efforts - forces and torque -and flows - rotary and translational motion [14]. We disagree with Hirtz et al's use of velocity since forces and torques do not cause velocity; they cause acceleration which has the result of a velocity at any instance in time. We use the term "Motion" to denote both acceleration and uniform velocity.

Table III Comparison of Hirtz et al's Translational and Rotational Motion with Structures and Mechanisms Sub-Sub-Domains

Pure ME	Translational		Rotational	
	Effort analogy	Flow analogy	Effort analogy	Flow analogy
Structures	Forces, moments Elastic and potential energy		Torques, Elastic and potential energy	
Mechanisms	Forces, moments, Elastic and potential energy	translational motion, kinetic energy	Torques, Elastic and potential energy	Rotational Motion, kinetic energy

This example of the mechanical engineering sub-domain illustrates our main thesis on its own. Namely that identifying the context surrounding a problem - the leaf of an engineering domain taxonomy - substantially restricts the availability of flows in the design space. We discuss this further below.

2.2 Functions and flows

The second part of context delimiting the problem area is that the each flow can be added to the domain context (viz the sub-domain, sub-sub-domain etc.) in which they are relevant to form a new context in which there are a limited number of functions that are associated with the new context (I.e. sub-sub-sub-domain plus flow). Hirtz et al have suggested this but did not pursue it further [14]. Again we need guiding principles and not just use ad-hoc decisions. In our approach we seek functions which make physical sense for the individual flows in a specific context (or flow leaf in the taxonomy). By this we mean that a combination of a function and a flow has to make physical sense or obey physical laws, principles or well know relationships: there must be some physical principle or law that connects the function with the flow. For example, Newton's second law connects force with linear acceleration or torque with rotational acceleration. In what follows we focus on the "Pure Mechanical Engineering" sub-sub-domain.

Table IV lists the mechanical engineering laws and principles that can be used for associating flows with functions in the mechanical engineering sub-domains. The laws are self explanatory. The principles require further explanations. There are many physical artefacts that could be cited in this part. For example, posts, beams, gears, springs. These are solutions not principles while the inclined plane and the lever are general physical principles on which many artefacts are based. St Venant's principle is well known and can be found in any solid mechanics book. Forces, torques etc are vectors and the rules governing their behaviour can be used as principles. Mechanical energy is manifested as strain energy and hence is governed by Hooke's law. For potential energy or kinetic energy this energy is contained in real bodies or entities. A geometric point has no mass and cannot have kinetic or potential energy. Thus it is impossible to separate the body from the energy and we use the equations for kinetic energy (KE) and potential energy (PE) as shorthand for this concept. For certain functions we then act on the body to perform the function on the energy flow. For other sub-domains of engineering other laws (E.g. Maxwell's equations and Ohm's law in Electrical Engineering) and principles will be involved.

Table IV Physical Laws and Principles used to Associate Functions with Flows

Laws	Principles
Newton's three laws	Inclined plane
Law of conservation of momentum	Levers
Law of conservation of energy	St Venant's principle
Laws of friction	Vectors
Law of Elasticity (Hooke's law)	$KE = ½ mv^2$
Law of Gravity	PE = mgh

We start by considering forces, moments and torques together as a single entity. The rational for this is that a moment is a force applied at a distance – the moment arm – from some point. Hence, a moment is basically a force. Torque is a moment applied along an axis. Thus a torque is similar to a force and we can deal with them together. In what follows we bold the functions that are applicable to the flow set and leave normal those that do not apply.

In the Hirtz paper the first category is **branch** [14]. A beam support at either end causes the force in the middle to branch to the supports. The physical principle is moment arm or lever. The next level is **separate** and **distribute**. The same physical principles apply. We also note that Newton's third law (i.e. action-reactions) applies in that a single point force applied vertically downward on any mass supported on some base plane is resisted by the reaction forces distributed across the base of the body: the face in contact with the ground plane. This is the application of St Venant's principle.

Under **separate** there are the correspondents isolate, sever and disjoin. There is no physical principle or law that the authors are aware of that can do these things to forces or torques. Under the tertiary level there is **divide**, extract, remove. Forces can be divided using the same principle as the secondary category. However in the correspondents associated with **divide**, only **split** has a similar meaning to divide. In our view it is not possible to extract or remove forces. Forces are abstract entities and have no physical presence except as actions on other bodies. Extraction or removal only applies to physical objects. None of the correspondents have significantly different meaning to these two.

The next item at the primary level is **channel**. **Channel** has several meanings as illustrated by the tertiary level functions and correspondents. All of them can only be applied to some physical entity. Since forces are not physical entities, they cannot be imported, exported, guided, or transferred. The only functions in this primary category that appear to have some meaning when applied to forces and torques are the tertiary flows "**transmit**" and "**translate**". If a force or a torque is applied to one part of a body and that body is connected to another body along the vector of the force, then in essence the force is "transmitted" or "translated" through the body to appear at the boundary between the two bodies. Similarly torque applied to one end of a shaft is "transmitted" or "translated" to the other end if the other end is connected to another body. The physical principle involved is elasticity. The force (or torque) creates displacements in the locations in the atoms or ions at the point of application of the force or torque, which cause displacements in the nearest neighbor atoms and so along the direction of the force until the atoms at the surface impinge on the neighboring body due to their displacements on the next body.

Under **connect**, the next primary category, coupling is only possible with physical entities. Under mix, forces and torques can be **added** to bodies and **combined** within bodies, but not blended, coalesced or packed which apply to physical material.

The "control magnitude" primary category mostly applies to signals and is not relevant to forces or torques. However lever arms or inclined planes can **"Increment"** and "**Decrement"** forces moment and torques. **"Increase"** and **"decrease"** have similar meanings to **increment** and **decrement** and thus must also be included. Forces, moments, and torques can also be "**changed"** by similar physical artefacts.

In the next primary flow category, forces and torques can certainly be **converted**: forces into torques and torques into forces using levers and wheels. They can also be converted from and to mechanical energy, and from and to motion. Most of the correspondents, however do not apply to abstract entities such as forces, torques and moments. The only correspondent that is equivalent to **convert** is **transform.** There are two other correspondents that apply, but is not clear why these are under the primary and secondary levels of convert: **Create** and **generate**. The prime entity is the force. If a force can be created or generated then they can be converted into moments and torques. Forces can be created or generated by several methods: human effort, springs (which is essentially converting elastic energy to a force), using gravity, through reaction forces between bodies (Newton's third law), electromagnetism, electrostatics, and friction. The applicable laws are self evident here. Forces can also be **created** and **generated** by rockets, gas turbines (also called jet engines) and propellers driven by some kind of engine. The applicable law for these methods is Newton's third law of action and reaction. The strong and weak nuclear interactions also can be used but are not considered here because of their extremely short range.

Table V Flows and Functions and Principles for Forces, Torques and Moments

Flow	Primary	Secondary	Tertiary	Correspondents	Physical Principle
Forces, torques moments	**Branch**	**Separate**			Lever and gears
			Divide	**Split**	levers, gears
		Distribute			St Venant's principle
	Channel	Transfer	**Transmit**		Elasticity
		Guide	**Translate**	**Move, relocate**	Elasticity
	Connect	Mix		**Add, combine**	Elasticity
	Control Magnitude		**Increase**		Levers, inclined planes
			Decrease		Levers, inclined planes
		Change	**Increment**	**Amplify, magnify,**	Levers
			Decrement	**Attenuate,**	Levers
	Convert	**Convert**		**Create, generate**	Misc
	Provision	**Supply**		**Provide**	See create
	Signal	Sense	**Detect**		Through Strain
			Measure	**Identify**	Through Strain
		Indicate			Through Strain

Under **Provision**, forces cannot be stored. Only mechanical energy is stored, see below. One may argue that a spring stores a force, but it is the elastic energy that is stored in a spring and it is released in the shape of a force or motion. Forces can neither be contained nor collected since they are not physical entities**.** Forces can be **supplied** or **provided** when the meaning of supply or provide is to create or generate, see above.

Signal applies mostly to information. However, a force, torque, etc can be **sensed, detected, measured, identified**, and **indicated** by the reaction of the body on which the force acts. A net force causes an acceleration of the body on which it acts. This motion can be detected by electrical, optical, or electromagnetic means.

A force or torque also causes a deformation or strain which can be **sensed, detected, measured, identified**, and **indicated** by strain gauges. This involves converting the strain into electrical signals.

The results of this analysis are presented in Table V. In this table we have eliminated from Hirtz et al's taxonomy [14] the functions that do not apply, keeping only the primary and secondary categories to remind us of the derivation of the lower level functions. Functions that are bolded are relevant. Non-bolded functions are left for completeness and show the derivation back to the primary function category.

The second flow is mechanical energy which can be classified into elastic, potential and kinetic energy. Using arguments similar to those above for forces, torques and moments, we arrive at the correlation between elastic energy and functions illustrated in Table VI. We have not distinguished between translational or rotational kinetic energy since we note that the functions themselves do not distinguish between them. For elastic energy and potential energy the distinction between rotational and translational is meaningless. Tables VII, and VIII illustrate the results of this analysis for potential energy and kinetic energy.

Table VI Flows and Functions and Principles for Elastic Energy

Flow	Primary	Secondary	Tertiary	Correspondents	Physical Principle
Elastic energy	Branch	Separate	**Divide**		Divide body
		Distribute			Joining multiple entities
	Channel	Import	**Transmit**		Conserve energy
	Connect	Mix		**Add, blend, combine**	Conserve energy
	Control Magnitude		**Increase**		Inclined plane/lever
			Decrease		Inclined plane/lever
		Change	**Increment**	**Amplify**	Inclined plane/lever
			Decrement	**Attenuate**	Inclined plane/lever
	Convert	**Convert**		**transform**	Hooke's law, Conserve energy
	Provision	**Store**			Hooke's law
		Supply		**Provide**	Hooke's law
	Signal		**Detect**		Through Strain
			Measure		Through Strain

Table VII Flows and Forces and Principles for Potential Energy

Flow	Primary	Secondary	Tertiary	Correspondents	Physical Principle
Potential energy	**Branch**	**Separate**			Law of gravity
			Divide		Law of gravity
		Distribute			Divide the body
	Channel	**Transfer**			Move the body
			Transport		Move the body
		Guide	**Translate**	**Move**	Move the body
			Rotate	**Spin, turn**	Move the body
	Connect	**Mix**		**Add, blend, combine**	Different types of energy
	Convert	**Convert**		**Transform**	Among different energy types, forces and energy
	Provision	**Store**		**Accumulate**	Add bodies
		Supply		**Provide**	Conserve Energy
	Signal		**Detect**	**Discern, perceive, recognize**	Height in field, PE=mgh
			Measure	**Identify, locate**	Height in field, PE=mgh

3 DISCUSSION

A major contention of this paper is that context in design delimits the problem space. We have focussed on the context defined by the domain or engineering discipline surrounding the design problem. By decomposing the engineering domain into sub-domains, sub-sub-domains etc., and using Hirtz et al's research, we have identified the flows associated with two sub-sub-sub-sub-domains, namely structures and mechanisms [14]. Table IX compares the number of flows in each of these with the total number of flows in the Hirtz et al's tables of flows. In the Hirtz et al enumeration we counted all the flows in the energy table then added the flows for materials and signal/information from the more general table. We did not count the words "Effort" and "flow" in the energy table. The reduction in the number of flows is approximately 95% for the sub-sub-domain of "Pure" mechanical engineering.

Table VIII Flows and Functions and Principles for Kinetic Energy

Flow	Primary	Secondary	Tertiary	Correspondents	Physical Principle
Kinetic energy	Branch	**Separate**			Divide the body,
			Divide		Divide the body,
		Distribute			Divide the body,
	Channel	**Transfer**			Move body
			Transport		Move body
			Transmit		Move body
		Guide	**Translate**	**Move, relocate**	Move body
			Rotate	**Spin, turn**	Move body
	Connect	**Mix**		**Add, blend, combine**	With other energy forms
	Control Magnitude		**Increase**		Increase body speed
			Decrease		Decrease body speed
		Change		**Scale, vary, modify**	Change body speed
			Increment	**Amplify,**	Increase body speed
			Decrement	**Attenuate**	Decrease body speed
	Convert	**Convert**		**Transform**	Among different types between energy and forces
	Provision	**Store**		**Accumulate**	$KE=1/2mv^2$
		Supply		**Provide**	$KE=1/2mv^2$
	Signal	**Sense**			Measure speed
			Detect	**Discern**	Measure speed
			Measure	**Identify**	Measure speed

We then used physical laws or principles to delimit the functions that might be associated with a particular flow or set of flows. Table X compares the total number of functions (including correspondents) in Hirtz et al with the functions associated with the flows; forces, torques and moments, and the three types of mechanical energies we have identified as relevant flows for our context. In Hirtz et al's work we counted all the separate functions in their combined table then added the list of those that appeared more than once [14]. While not as substantial a reduction as with the flows, the average reduction is 71%. When we combine the data from tables V thru VII into structures and mechanisms and compose it up one further level to "Pure" Mechanical Engineering, we find the results in Table XI which also has the composed results for the flows.. To compute these numbers we counted each of the functions and flows that occur multiple times once, then added the count of functions and flows that only occur once. For the sub-sub-sub-domains of structures and mechanisms similar results are obtained. Tables IX, X and XI strongly support our contention that context delimits the problem space.

Table IX Comparison of flows in main domain and sub-sub-domains

Flow source	**Hirtz et al**	**Structures**	**Mechanisms**
No of flows	96	4	6
Percentage decrease		96%	94%

Table X Comparison of Number of functions Associated with Different Flows

Function source	Hirtz et al	Forces, moments torques	Elastic energy flow	Potential energy flow	Kinetic energy flow	Motion
No functions	112	28	19	28	37	50
Percentage decrease		75%	83%	75%	67%	55%

Table XI Comparison of Number of Functions Associated with "Pure" Mechanical Engineering

Function Source	Hirtz et al	Pure Mechanical Engineering
No functions	112	61
Percentage decrease		55%
No Flows	96	6
Percentage decrease		94%

One may argue with the restrictions of the number of flows and functions. There is certainly room for debate on the functions. We do not believe that our list presented above for the various flows is final. This topic will be ongoing research for some time. However, for the flows it is fairly clear that there will not be many more unless another researcher finds a physical principle that allows materials and information into "Pure" mechanical engineering. In our view, "Pure" mechanical engineering uses materials and information but does not perform functions on them. That happens in the Materials domain. It might be argued in mechanisms that information may be needed to control the mechanism, In this case, we believe the domain context switches to the controls sub-sub-domain and is no longer in "Pure" mechanical engineering. However, if any researcher objects to a particular function being included with some flow, then removing it would further substantiate our claim. Adding one or two more functions to the list of functions will certain decrease the percentage reductions but will not substantially change our contention.

Another premise we suggested was that if a designer can identify the domain in which the design problem lies, they will have a restricted set of flows to work with and this would simplify the design. Indeed, we also contended that experienced engineers do exactly that. The issue then is how a designer identifies the domain. In our view experienced designers identify domains most likely by knowing the flows they are working with. First, designers have specific disciplines in which they were trained. A mechanical engineer rarely is presented with a design problem involving power electricity. If this happens in a small company for example, since the designer is the only design person they have, a competent mechanical engineer will immediately seek outside help. At the next level, the mechanical engineer is trained in a variety of disciplines: structures, mechanisms, fluids, heat transfer etc. We believe that this training starts them on the path of recognizing the domain context of the problem. Experienced engineers quickly recognize that in these different disciplines they are dealing with different flows. However, current training does not emphasize this and young engineers learn to do this as part of their practical on the job training. Perhaps this approach of identifying flows could be incorporated into the classroom.

For example, an experienced mechanical engineer faced with a problem concerned with supporting some load in space knows that he is dealing with flow of forces and moments but no motion. He is therefore in the sub-sub-sub-domain of structures with the further limitation that kinetic energy is also not relevant. This limits him/her to the functions in Table V. If they are faced with a problem in which they have to provide some prescribed motion, they are in the domain of mechanisms. An inexperienced engineer may not recognize which flow they are dealing with and consider a much larger range of functions, which will hinder decision making. They examine a large number of irrelevant flows before finally realizing that they can only consider a few. This train of thought then leads to the idea that perhaps the context is not defined by the domains, sub-domains etc but by the flows themselves. This is an area for further research.

One major problem with our approach is that not all designers or design educators subscribe to the systematic approach of Pahl and Beitz. There are a large number of successful designers who do not subscribe to this approach. There is also the existence of the holistic design approach in which solutions spring into mind complete in all its aspects. This is rare and wonderful when it happens but usually only occurs with experienced designers. It does not help a young, inexperienced designer learn how to do design. Further, there is increasing emphasis on multi-disciplinary design in which designer from multiple disciplines collaborate to design something that incorporates software, electrical and mechanical aspects. The fact that such people and approaches exist does not negate the systematic approach or the ideas in this paper. Experienced designers will continue to design by the methods they have learned in the past. Designers faced with multidisciplinary design problems invariably decompose, mostly by function. Most often they end up with single discipline design problems.

If flows really define the domains, sub-domains, etc as suggested above, it may be possible that a alternative approach to design problems is to focus on identifying and decomposing the flows rather than the functions as suggested by Pahl and Beitz [16]. This is controversial to say the least and will not be discussed further. It is left as a suggestion for future discussion.

Working with the principles to identify possible functions for a particular flow revealed to the authors that there were some discrepancies in correspondents, tertiary and secondary functions in Hirtz et al's taxonomy [14] when they were viewed from this perspective. This led to the thought that perhaps a better way of classifying functions might be by the physical laws and principles. We are exploring this idea further.

A related concept that has emerged from our research is that the "leaves" of the flow and function taxonomies illustrated are not really leaves but simply nodes and that by decomposing more using a different principle, one can create leaves that point to a more or less unique solution. We have explored this in the structures context. We postulate the concept of a ground plane (similar to that used in designing mechanisms). The presence or absence of it leads to categorization of structures. Those with a ground plane based on the planet earth may use Newton's third law to create reaction forces from the ground plane. Design problems without an earth based ground plane (e.g. a space station) require other solutions such as rockets. The location of the ground plane creates further subcategories. If our design problem is to support some body in space and there is a ground plane directly below the location of the load then a column is the most likely solution. If the ground plane is above then a tie (or more) is the best solution. Mechanisms can possibly be further subdivided by the properties of the flow. This is where Hirtz et al's categorization of motion into translation and rotation comes in. These characterizations are *properties* of the flow. Within the rotational branch of the taxonomy the magnitude and direction of the input and output vectors (i.e. torque of rotational velocity) guide one to deciding whether a spur, helical, crossed helical or work gear is the correct solution.

The taxonomies presented above could form the basis of an automated system for guiding inexperienced designers to the restricted flows and functions for their domain context. Conceptually, this system would lead a user through a series of menus. At each selection, the new menu would depend on the item selected in the previous menu, until the leaf is reached. We suggest that it might be possible to have leaves of such a system that proposed a limited number of possible solutions (i.e. one or two), thereby automating much of design decision making. Such a system would guide inexperienced engineers through the process of identifying flows, properties of flows until a solution is reached.

4 CONCLUSIONS

We believe that the data presented above proves our contention – at least in the limited sub-sub-sub-domains explored – that the domain context severely prunes the number of functions and flows that need be considered by a designer faced with some design problem. However, we do not believe that this paper will be the last word. There will undoubtedly be some debate over whether this or that function needs to be included in this or that domain. This result would be ideal since one of our purposes for this paper is to spark discussion of this way of looking at the design problem and context. We have also suggested a number of areas for further research some of which we are exploring ourselves.

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